

## Feedback from Winds and Supernovae in Massive Stellar Clusters

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**Abstract.** We simulate the effects of massive star feedback, via winds and SNe, on inhomogeneous molecular material left over from the formation of a massive stellar cluster. We use 3D hydrodynamic models with a temperature dependent average particle mass to model the separate molecular, atomic, and ionized phases. We find that the winds blow out of the molecular clump along low-density channels, and gradually ablate denser material into these. However, the dense molecular gas is surprisingly long-lived and is not immediately affected by the first star in the cluster exploding.

### 1. Introduction

Massive stars dramatically affect the interstellar medium surrounding them, through their powerful winds, radiation fields and terminal explosions. Their influence can extend to extra-galactic scales, with groups of massive stars able to pressurize kpc-scale superbubbles which can vent into the inter-galactic medium. This “feedback” can alter the evolution of the host galaxy. The current consensus is that momentum and energy from stellar winds and supernovae plays a key role in suppressing star formation in lower mass dark matter haloes, thus explaining the lack of faint galaxies relative to bright galaxies (White & Rees 1978).

However, the degree to which these stellar inputs couple to the clumpy, inhomogeneous molecular clouds which initially surround a massive stellar cluster is exceedingly ill-determined. Even the dominant feedback process continues to be debated (e.g. Yorke et al. 1989; Draine & Woods 1991; Matzner 2002; Wang et al. 2010; Lopez et al. 2011). Chandra X-ray and Spitzer infrared observations of clusters of young stars have shown that the surrounding cold molecular can sometimes confine the hot gas created by the stars (e.g. Townsley et al. 2006), yet in other clusters the cold clouds appear to be shaped and removed by the hot gas (see, e.g., Townsley et al. 2003). Most simulations of stellar feedback continue to adopt a uniform ambient medium (e.g. Freyer, Hensler & Yorke 2003; Toalá & Arthur 2011) - those that do not generally focus on the impact of massive star feedback on local star formation (e.g. Peters et al. 2010), rather than larger-scale effects.

There are several competing models for stellar wind feedback. In the model of Castor, McCray & Weaver (1975) - see also Dyson & de Vries (1972) and Weaver et al. (1977) - the shocked stellar wind is confined by a cool shell of swept-up interstellar gas. In contrast, Chevalier & Clegg (1985) ignored any surrounding material and simply assumed a steady-state wind extending to infinity. The temperatures and pressures of the resulting structures are significantly different. More recently, Harper-Clark & Murray (2009) have examined a third scenario in which breaks in the swept-up shell

allow some of the hot high-pressure gas in the bubble interior to leak out. This situation is expected to occur when the surrounding environment is highly structured, such as in massive star forming regions. A recent analysis of the pressures of various components inside the giant HII region 30 Doradus implied that such leakage is occurring (Lopez et al. 2011). However, the wider picture is not so clear. Models of the collisions of multiple stellar winds within a star cluster have also been created (e.g. Rodríguez-González et al. 2008; Reyes-Iturbide et al. 2009), though key processes including particle acceleration at the multiple shocks within the cluster (e.g. Domingo-Santamaría & Torres 2006) and mass-loading from the cold clouds embedded within it (e.g. Tsivilev et al. 2002; Bruhweiler et al. 2010) have been neglected to date.

The effects of the ionizing radiation from massive stars were studied by Tenorio-Tagle (1979), who found that an O-star near the edge of a molecular cloud creates a high pressure HII region around itself which can burst out of the cloud as a “champagne” flow. Whitworth (1979) and Bodenheimer, Tenorio-Tagle & Yorke (1979) showed that champagne flows could efficiently disrupt the molecular cloud, though Mazurek (1980) and Yorke et al. (1989) argued that the dispersal of clouds is dramatically reduced if the clouds are in free-fall and the ionizing sources are located near their centres. More recent work has shown that ionization feedback into a highly inhomogeneous medium may not be very effective (e.g. Mac Low et al. 2007; Peters et al. 2010; Krumholz et al. 2010; Dale & Bonnell 2011).

The effect of a supernova explosion on a molecular clump was investigated by Tenorio-Tagle, Bodenheimer & Yorke (1985), who concluded that a single supernova could disrupt  $\sim 10^4 M_\odot$  of molecular cloud material. However, it is not clear how this inference might change if the surrounding material is clumpy.

## 2. Numerical Models

We have constructed 3D hydrodynamical models of the collective influence of stellar winds and supernovae from the stars in a massive stellar cluster on the molecular, atomic, and ionized gas within and external to the cluster-forming GMC clump. A key difference with some earlier works is that we do not assume that the initial ambient medium is uniform and stationary. Instead, for our initial conditions we adopt the simulation results of Vázquez-Semadeni et al. (2008) of turbulent and clumpy molecular clouds (specifically model Ms24J6). We scale these results to create a GMC clump of radius 5 pc and mass  $5000 M_\odot$ . The clump initially has a uniform temperature of about 10 K, and is in rough pressure equilibrium with a surrounding uniform medium of density  $3.33 \times 10^{-25} \text{ g cm}^{-3}$  and temperature 8000 K. The mechanical feedback from the stellar cluster is assumed to be dominated by three  $40 M_\odot$  stars situated at the centre of the clump which collectively drive a cluster wind with a mass-loss rate  $\dot{M}_{\text{cl}} = 1.5 \times 10^{-6} M_\odot \text{ yr}^{-1}$  and velocity  $v_{\text{cl}} = 2000 \text{ km s}^{-1}$ . After 4.0 Myr the cluster wind is assumed to be dominated by red-super-giant material, and has  $\dot{M}_{\text{cl}} = 3 \times 10^{-4} M_\odot \text{ yr}^{-1}$  and  $v_{\text{cl}} = 50 \text{ km s}^{-1}$ . The cluster wind transitions to a Wolf-Rayet dominated phase after 4.2 Myr with  $\dot{M}_{\text{cl}} = 6 \times 10^{-5} M_\odot \text{ yr}^{-1}$  and  $v_{\text{cl}} = 2000 \text{ km s}^{-1}$ , after which the first SN explosion (of  $10^{51}$  ergs energy and  $10 M_\odot$  ejecta) occurs.

The hydrodynamic grid covers a cubic region of  $\pm 16 \text{ pc}$  extent centered on the GMC clump and contains  $512^3$  cells. The cluster wind is injected as purely thermal energy within a radius of 0.375 pc (6 cells). A uniform heating rate of  $10^{-26} \text{ erg s}^{-1}$  is



Figure 1. Density slices through the 3D simulation at  $t = 0.1, 0.3$  and  $1.0$  Myr. White is high density and black is lower density.

used, together with a cooling curve designed to give 3 stable thermal phases at  $\sim 10, 100$ , and  $8000$  K (see Pittard 2011, for further details). The average particle mass in the simulations is temperature dependent and determined by a look-up table (see Sutherland 2010). The densest regions cool to  $1$  K, which is the imposed temperature floor. Our simulations do not include gravity, thermal conduction or magnetic fields.

### 3. Results

The cluster wind creates a high-temperature bubble within the GMC clump which expands most rapidly into regions of lower density and pressure. Fig. 1 shows the early evolution of this process. The cluster wind breaks out of the GMC clump wherever it can find channels of low resistance. This break out ejects fragments of the shell of GMC clump material swept up by the winds. Clump material along the walls of these channels is ablated into the flow so that the clump gradually loses mass. A wide variety of densities and temperatures exists throughout the clump, with each covering in excess of 7 orders of magnitude. A strong reverse shock heats the cluster wind near its source, while many weaker shocks exist within the flow as the surrounding dense regions collimate its passage. Slow shocks are transmitted into dense clump material, which is compressed by the high pressure wind. Dense parts of the clump can shield and protect less dense material in their “shadow”, though the ability of the hot, high pressure, gas to flow around denser objects mitigates this effect to some extent.

As lower density material is gradually cleared out of the clump, the dense clouds slowly become isolated from each other, and find themselves exposed more forcefully to streams of hot, fast-flowing, gas. The material ablated from the clouds forms distinct tails. The lower dynamic pressure of the RSG-dominated cluster wind between  $4.0$  and  $4.2$  Myrs slightly reduces the hydrodynamic ablation rate of the clump. This reprieve is short-lived, however, as the cluster wind becomes significantly more powerful when the stars enter their WR stage. We find that the GMC clump loses mass at a roughly constant rate from  $t = 0.0$  up to the end of the WR stage ( $t = 4.5$  Myr), with the mass of molecular material declining from  $5000 M_{\odot}$  to  $1800 M_{\odot}$  over this period.

The reverse shock in the cluster wind is far from spherical. Its shape is strongly influenced by the presence of nearby dense clouds around which the cluster wind forms

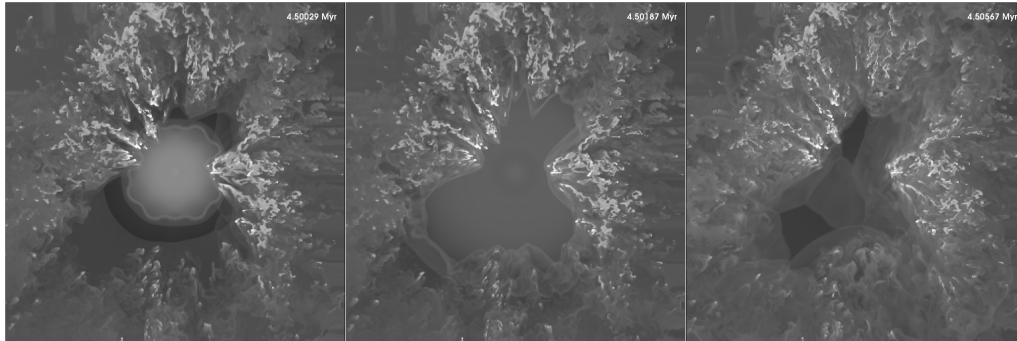


Figure 2. Density slices through the 3D simulation at 960, 2540 and 6340 yrs after the first star explodes as a supernova. White is high density and black is lower density.

bowshocks. At  $t = 4.5$  Myr the reverse shock has a typical radius of 2.5 pc, with the nearest dense clouds about 1.5 pc from the centre of the cluster.

Fig. 2 shows the time evolution of a density slice through the cluster shortly after a SN explosion (occurring at  $t = 4.49933$  Myr) which deposits  $10 M_{\odot}$  of ejecta and  $10^{51}$  erg of energy into the surroundings. The SN ejecta sweeps up the WR-dominated cluster wind into a thick, adiabatic shell. This shell propagates at high speed through the lower density regions surrounding the explosion, and refracts around the dense clouds which it encounters. Transmitted shocks move into the dense clouds while reflected shocks move backwards towards the explosion site and converge in a highly asymmetric fashion due to the azimuthally dependent distribution of the nearest dense clouds. The early evolution of the supernova remnant (SNR) is hence very different to the standard, spherically symmetric, picture. Our simulations currently end at  $t = 4.75$  Myr. The passage of the SNR appears to have had very little immediate effect on the dense clouds.

#### 4. Conclusions and Future work

Our preliminary analysis reveals that stellar wind feedback in massive stellar clusters is a complex process which is strongly affected by the inhomogeneity of the gas within the remains of the cluster-forming GMC clump. The resulting structures and their evolution are far removed from the results of simple spherically symmetric models. Hot, high speed gas flows away from the cluster in low-density channels opened up by the stellar winds. Mass is loaded into these flows from the ablation of dense clouds embedded within them and from material stripped from the dense gas which confines and directs the flows. The rate of ablation appears to be roughly constant during the first few Myr of the cluster evolution. About half the initial molecular mass remains by the time the first SN occurs (at 4.5 Myr in our model). The high porosity of the dense molecular material at this stage allows the SN blast to rip through the cluster in a largely unimpeded fashion, with the forward shock refracting around dense inhomogeneities. The passage of the shock appears to have little immediate effect on the remaining dense clouds.

A detailed analysis of our results is currently underway. However, it would seem that stellar winds, like ionizing radiation fields (Dale & Bonnell 2011), couple relatively weakly to the dense gas in such environments. In a similar vein, the disruption of molecular clouds by supernovae may also be weaker than previously anticipated.

Future work will examine massive star feedback on a variety of GMC clump sizes, and will include the effects of magnetic fields, thermal conduction and gravity.

**Acknowledgments.** JMP would like to thank The Royal Society for funding a University Research Fellowship.

## References

- Bodenheimer, P., Tenorio-Tagle, G., Yorke, H. W. 1979, *ApJ*, 233, 85  
 Bruhweiler, F. C., Freire Ferrero, R., Bourdin, M. O., Gull, T. R. 2010, *ApJ*, 719, 1872  
 Castor, J., McCray, R., Weaver, R. 1975, *ApJ*, 200, L107  
 Chevalier, R. A., Clegg, A. W. 1985, *Nature*, 317, 44  
 Dale, J. E., Bonnell, I. 2011, *MNRAS*, 414, 321  
 Domingo-Santamaría, E., Torres, D. F. 2006, *A&A*, 448, 613  
 Draine, B. T., Woods, D. T. 1991, *ApJ*, 383, 621  
 Dyson, J. E., de Vries, J. 1972, *A&A*, 20, 223  
 Efsthathiou, G. 2000, *MNRAS*, 317, 697  
 Freyer, T., Hensler, G., Yorke, H. W. 2003, *ApJ*, 594, 888  
 Harper-Clark, E., Murray, N. 2009, *ApJ*, 693, 1696  
 Krumholz, M. R., Cunningham, A. J., Klein, R. I., McKee, C. F. 2010, *ApJ*, 713, 1120  
 Lopez, L. A., Krumholz, M. R., Bolatto, A. D., Prochaska, J. X., Ramirez-Ruiz, E. 2011, *ApJ*, 731, 91  
 Mac Low, M.-M., Toraskar, J., Oishi, J. S., Abel, T. 2007, *ApJ*, 668, 980  
 Matzner, C. D. 2002, *ApJ*, 566, 302  
 Mazurek, T. J. 1980, *A&A*, 90, 65  
 McKee, C. F., Ostriker, J. P. 1977, *ApJ*, 218, 148  
 Mellema, G., Arthur, S. J., Henney, W. J., Iliev, I. T., Shapiro, P. R. 2006, *ApJ*, 647, 397  
 Peters, T., Klessen, R. S., Mac Low, M.-M., Banerjee, R. 2010, *ApJ*, 725, 134  
 Pittard, J. M. 2011, *MNRAS*, 411, L41  
 Reyes-Iturbide, J., Velázquez, P. F., Rosado, M., Rodríguez-González, A., González, R. F., Esquivel, A. 2009, *MNRAS*, 394, 1009  
 Rodríguez-González, A., Esquivel, A., Raga, A. C., Cantó, J. 2008, *ApJ*, 684, 1384  
 Sutherland, R. S. 2010, *Ap&SS*, 327, 173  
 Tenorio-Tagle, G. 1979, *A&A*, 71, 59  
 Tenorio-Tagle, G., Bodenheimer, P., Yorke, H. W. 1985, *A&A*, 145, 70  
 Tsvilev, A. P., Poppi, S., Cortiglioni, S., Palumbo, G. G. C., Orsini, M., Maccaferri, G. 2002, *New Astr.*, 7, 449  
 Toalá, J. A., Arthur, S. J. 2011, *ApJ*, 737, 100  
 Townsley, L. K., Feigelson, E. D., Montmerle, T., Broos, P. S., Chu, Y.-H., Garmire, G. P. 2003, *ApJ*, 593, 874  
 Townsley, L. K., Broos, P. S., Feigelson, E. D., Garmire, G. P., Getman, K. V. 2006, *AJ*, 131, 2140  
 Vázquez-Semadeni, E., González, R. F., Ballesteros-Paredes, J., Gazol, A., Kim, J. 2008, *MNRAS*, 390, 769  
 Wang, P., Li, Z.-Y., Abel, T., Nakamura, F. 2010, *ApJ*, 709, 27  
 Weaver, R., McCray, R., Castor, J., Shapiro, P., Moore, R. 1977, *ApJ*, 218, 377  
 White, S. D. M., Rees, M. J. 1978, *MNRAS*, 183, 341  
 Whitworth, A. 1979, *MNRAS*, 186, 59  
 Yorke, H. W., Tenorio-Tagle, G., Bodenheimer, P., Rozyczka, M. 1989, *A&A*, 216, 207